Abstract

Hydrogen-like muonic atoms are Coulomb bound states of a muon and a hadron. In ultrarelativistic heavy-ion collisions, due to the high particle multiplicities, a produced muon can be directly bound to a charged hadron, and form an atom. Among these atoms, the antimatter muonic hydrogen and the K–µ atom have been predicted but not yet been discovered. With muon identification at low transverse momentum from the Time-of-Flight detector, STAR provides a great opportunity to search for these exotic states. A typical event at STAR shows sharp peaks at the expected position. The corresponding kaons and protons are at TOF comfortable ranges as shown above.

Invariant Mass

Invariant mass background is studied with two background subtraction methods: Mixed-Event (ME) Method and Like-Sign (LS) Method. The LS background is then corrected for acceptance difference between like-sign and unlike-sign pairs.

\[ \text{LS}_{\text{corrected}} = \frac{\text{ME}_{+}}{\text{ME}_{-}} \]

- Like-sign and Unlike-Sign have opposite Coulomb forces. The product cancels the major effect \( S_{\text{ES}} \times \text{LS}_{\text{corrected}}/\text{ME}_{+} \).

The invariant mass distributions of K-µ pairs show peaks at the expected position (0 net mass).

Search for Antimatter Muonic Hydrogen at STAR
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Two Particle Correlations

- \( k^* \) – the magnitude of the three-momentum of either particle in the pair rest frame.
- \( C(k^*) \) – the ratio of the \( k^* \) distribution constructed from particles from the same events to that from particles from mixed events. Correlation functions show the existence of Coulomb force which is required by atom formation.

Particle Identification

The data set used is \( N_{\text{Au-Au}} \sim 200 \text{GeV} \) Au+Au central events in Run 10. A total of 230 million events have been analyzed. The two main detectors for particle identification are the Time-Projection Chamber and the Time-Of-Flight Detector. Low transverse momentum muons are identified by first applying a tight TPC cut, then applying the TOF cut. The purity of the muon sample used in this analysis is 99%.

The corresponding kaons and protons are at TOF comfortable ranges as shown above.

π-µ Atoms

To form atoms, two particles from the same atom must be close in phase-space, i.e. \[ \alpha = \frac{p_x - p_x^*}{p_x + p_x^*} = \frac{m_{a^*} - m_a}{m_{a^*} + m_a} \approx \frac{m_a - m_a}{m_{a^*} + m_a} = 0.14 \]

Pion-muon atoms have been observed in K- decay at Fermilab[9] and BNL[10]. However antimatter/strange muonic atoms have not yet been discovered.

Estimations at STAR

A typical event at STAR shows a 1.77 GeV/c charged particle produced and identified. Atoms formed at the collision point, disassociated by beam pipe (ionization).

Atom formation occurs well after freeze-out through particle coalescence. It is only sensitive to the particle distributions at freeze-out \[ \frac{dN_{\text{atom}}}{dy dp_{1,2,3}} = 8\pi \frac{\Gamma(\lambda)^2}{\alpha^2} \frac{1}{m_{a^*}} \frac{dN_{\pi}}{dy dp_{1,2,3}} \frac{dN_{\mu}}{dy dp_{1,2,3}}. \] \[ (1) \]

Muonic atom yields estimation with muon momentum accessible to STAR, calculated with STAR acceptance and the formula (1)[18].

\[ p_{1,2} \] ranges for muonic atoms accessible to STAR[13].

With the large amount of early produced (anti-)hadrons and muons, RHIC is able to produce all six of the above (anti-)atoms.

References
2. Coombes et al., Phys. Rev. Lett. 37, 249 (1976);
4. J. Kapusta, A. Mocsy, Phys. Rev. C 59, 2937 (1998);
5. 2010 STAR Decadal Plan;

Summary

We have observed two possible signatures of the new (antimatter) atoms:
- Invariant mass enhancement is observed at the expected mass for both K-µ and p-µ pairs.
- Muons and kaons that are close to each other in phase space are emitted simultaneously, suggestive of atoms.